RI 8478

Bureau of Mines Report of Investigations/1980

NEWARK PUBLIC LIBRARY

DEC 17 1980

U. S. GOVT. PUBS.
DEPOSITORY 376

Controlled Burnout of Wasted Coal on Abandoned Coal Mine Lands

By Robert F. Chaiken

UNITED STATES DEPARTMENT OF THE INTERIOR

I 28.23.

Report of Investigations 8478

Controlled Burnout of Wasted Coal on Abandoned Coal Mine Lands

By Robert F. Chaiken

UNITED STATES DEPARTMENT OF THE INTERIOR
Cecil D. Andrus, Secretary

BUREAU OF MINES
Lindsay D. Norman, Director

best copy available

This publication has been cataloged as follows:

Chaiken, Robert F

Controlled burnout of wasted coal on abandoned coal mine lands.

(Bureau of mines report of investigations ; 8478.)
Bibliography: p. 22-23.
Supt. of Docs. no.: I 28.23:8478.

1. Coal gasification, Underground. 2. Coal mines and mining—Environmental aspects. 3. Heat recovery. I. Title. II. Series: United States. Bureau of Mines. Report of investigations ; 8478.

TN23.U43 [TP759] 622s [665.7'72] 80-607100

CONTENTS

	Page
Abstract	1
Introduction	1
Extinguishment of fires in wasted coals	3
Conventional approaches to fire control	3
Burnout control of wasted coal	4
In situ combustion of coal	5
Application of in situ combustion to burnout control of wasted coal fires	7
Minimum combustible content for a coal refuse fire	7
Heat loss from channel burning in abandoned coal mines	9
Effective burn control volume in a waste bank	12
Effective burn control volume in an abandoned mine	14
Fan power requirements for burnout control	16
Surface transfer of hot exhaust products	17
Conclusions	21
References	22

ILLUSTRATIONS

1.	Data time plots for simulated in situ burn of rubblized coal	6
2.	Exhaust temperature as a function of coal and water content	9
3.	Model coal seam combustion channel	10
4.	Variation of fractional heat loss and exhaust temperature with channel-size scaling factor	11
5.	Two possible borehole arrangements	12
6.	Distance of negative pressure effect in a coal waste pile	14
7.	Efficiency of heat transport in a pipe	19
8.	Pressure drop versus pipe distance for transporting thermal power	21

TABLE

1.	Input data for numerical calculations	12

CONTROLLED BURNOUT OF WASTED COAL ON ABANDONED COAL MINE LANDS

by

Robert F. Chaiken[1]

ABSTRACT

A novel approach to eliminating environmental and public safety hazards that are associated with fires in abandoned coal mines and waste banks involves the use of in situ combustion technology developed by the Federal Bureau of Mines to accelerate the burning of the wasted coals in place. This technology would be used under exhaust ventilation control conditions that would allow for total management of the hot gases produced. Combustion stoichiometries would be optimized to minimize unburnt combustibles and to maximize the heat content of the gas products, which will be exhausted at one or more fan locations. When necessary, scrubber systems would be employed to remove air pollutants, such as sulfur dioxide; heat utilization systems (process heat, steam, and electricity) would also be employed to offset operational costs. Ultimately, complete burnout would solve the fire and acid water formation problems of the abandoned coal mine or waste bank.

Pertinent technical data for burnout control are derived and discussed in terms of the important material and operational parameters. In general, it is believed feasible to operate a burnout system in an existing abandoned mine or waste bank fire at thermal power levels in the range of 10 to 100 Mw, and at exhaust gas temperatures of 1,000° C (1,830° F).

INTRODUCTION

A significant aspect of all past and current coal mining is wasted coal. Wasted coal occurs in abandoned mines, which, because of the exigencies of underground mining operations, often contain as much coal as was extracted; and coal refuse piles, which are accumulations on the surface of reject material from coal preparation plants and from underground mining operations. Individual refuse piles (or waste banks) may contain millions of cubic yards

[1]Supervisory research chemist, Pittsburgh Research Center, Pittsburgh, Pa.

READEX FICHE

of solid waste, with a combustible content ranging from 15 to 50 pct by weight.[2]

Fires continue to occur in this wasted coal, introducing significant hazards to public health and safety, such as emissions of toxic and obnoxious fumes to the atmosphere and destruction of residential and commercial buildings. Once established, these fires can smolder for decades, and extinguishing them by conventional methods of sealing, dig-out, and quench is costly and hazardous (8-13).[3]

The magnitude of the problem can be appreciated by examining the cost estimates for extinguishing the wasted coal fires on abandoned lands (9). In a 1968 survey by the Bureau, 292 waste banks were found to be on fire and involved about 270 million tons of refuse and 3,200 acres of land. In a 1977 survey, 261 coal deposits were classified as burning. It has been estimated that the cost of extinguishing the 292 burning waste banks would be $468 million, and the cost of controlling the 261 fires in active coal deposits would be $75.6 million. These estimates of $1 million per fire are for fix-up only--they do not remove the fire potential of the wasted coal, nor do they include the effective value of the wasted coal if it could be utilized during the extinguishment and reclamation process.

The 3,200 acres of waste banks on fire, assuming a 20-wt-pct combustible content, would contain an estimated 54 million tons of coal, with a heating value of 10^{15} Btu, or 1 quad. This is equivalent to 1.4 pct of current annual U.S. energy use. Even with a 30-pct resource recovery and a selling price of $\$1/10^6$ Btu, the market value for the wasted coal would be $300 million, an amount approaching the cost of conventional extinguishment. It is difficult to estimate the tonnage of coal involved in the 261 coal deposit fires; however, it is not unreasonable to assume that the market value of the heat from the coal also would be comparable to the cost of conventional fire control.

Although the intrinsic public health and safety benefits of controlling fires on abandoned coal mined lands cannot be denied, neither can the high costs of conventional control techniques be ignored. Such costs present a serious constraint on how much and how fast corrective action can be accomplished. But if fire extinguishment and alleviation of environmental problems can be carried out simultaneously with conversion of wasted coal to a useful resource, the cost constraints would be reduced (or even eliminated), and an important new energy resource would be made available. This is the objective of a new Federal Bureau of Mines research and development program for eliminating the environmental problems of fires in abandoned coal mines and coal

---

[2]Because coal pillars remaining underground are useful for roof support and subsidence abatement, and because much of the coal in preparation plant refuse results from removal of undesirable matter from mined-out material, it could be argued that the coal is not really wasted. However, in terms of total resource recovery, these coals do represent an inefficiency in the extraction processes, as well as an environmental problem.

[3]Underlined numbers in parentheses refer to items in the list of references at the end of this report.

waste banks. This report describes some of the background for the new research and development.

EXTINGUISHMENT OF FIRES IN WASTED COALS

For any fire, the three essential components, fuel, heat and oxygen or air, are required. The removal of any one of these components will lead to extinguishment of the fire. For many years, the Bureau's efforts at extinguishing wasted coal fires has centered on removal of heat by water quenching and the removal of air by sealing (8, 10-13). This conventional approach is the basis of most firefighting techniques, whether it be for mine, building, room, or rubble fires. A possible exception to these firefighting methods is the backburning of trees and shrubs in the control of forest fires, so as to remove fuel from the path of an advancing fire front. The concept of burnout control of fire in wasted coal is also based on the removal of fuel: the burning of the wasted coal is accelerated, but in a way that allows total control of the heat and fumes produced. However, before discussing the burnout concept in detail, it is important to understand the more conventional fire control techniques and some of the problems involved with their application.

Conventional Approaches to Fire Control

The conventional approach to extinguishing fires in wasted coals involves excluding oxygen from the burning fuel and cooling the hot material to ground temperature (8, 10-13). With a well-established wasted coal fire, this becomes a herculean task. Each ton of affected material at a nominal temperature of 482° C (900° F) will have a sensible heat content of approximately one-half million Btu. To remove this heat rapidly by water cooling requires a minimum of about 65 gal to be applied uniformly over the hot combustible. Because of the possibility of a water-gas reaction which would produce explosive hydrogen gas, rapid quenching of a hot waste bank with water could be hazardous. Also, the difficulty of obtaining a uniform application of water in many wasted coal geometries, particularly in abandoned mines, adds to the difficulties and hazards of extinguishment.

There are three conventional fire control methods for coal waste banks: (1) dig-out and cool the affected material, (2) surface cover the waste pile to seal the pile against internal air circulation (i.e., oxygen exclusion), and (3) grout to solidify the affected material (also oxygen exclusion). Although these methods are cumbersome and costly, they are effective (8, 10-13).

The first method of fire control is the fastest and most effective, but also the most hazardous, for it requires considerable movement of hot material from one place to another. Material handling costs are high, and sometimes suitable land areas nearby may not be available for spreading the cooled wastes.

The second and third techniques involve a slow cool-down process by dissipation of heat through the sealing material (insulating cover or grout).

Thus, the surface of the pile requires many years of maintenance against weathering to insure the effectiveness of the air-exclusion technique.

Abandoned mine fires are even more difficult to control because of their inaccessibility and the sometimes great areal extent of the workings. The conventional approach to fire control is first, to contain the burning mined-out areas, and second, to exclude air from the burning coal. When the ground cover is shallow, isolation can be accomplished by constructing a trench from the surface to a level below the coal seam, and then backfilling the trench with inert material. Alternatively, fire barriers can be constructed by injecting wet or dry fly ash, or other readily available inert material, into the mine entries through boreholes. The surface above the isolated burning area is then cleared and sealed by plowing over and compacting the ground. The objective is to prevent atmospheric breathing, that is, flow of air through cracks and crevices because of changes in barometric pressure and/or thermally induced circulation flows. As in sealed waste piles, heat dissipation is very slow, so that the surface seals require long-term maintenance to be effective.

The major problem with the isolation and surface sealing technique for underground fires is the handling of enormous quantities of material. For example, a 60-foot-deep isolation trench will require digging out and backfilling about 180,000 tons of ground cover for every 1,000 feet of trench length. This is in addition to the material handling involved in surface sealing and upkeep of the acreage above the fire area.

Burnout Control of Wasted Coal

In recent years the Bureau has been examining the in situ combustion of coal in some detail (2, 4-5) and offers a possible alternative approach to the control of active fires in wasted coals. The approach envisioned involves the controlled acceleration of the fire by air injection so that complete fuel removal is accomplished in a relatively short time, compared with a normal waste coal burntime, that is, many decades. By developing burn channels in abandoned mine workings and in coal refuse piles, it should be possible to effect a complete controlled burnout of the coal and all other nearby combustibles, such as the carbonaceous rock materials and the pyrites. Unlike all previous underground coal burning systems (e.g., in situ coal gasification), injection of air and removal of combustion products would be accomplished by exhaust ventilation from the surface. This approach has a number of distinct advantages:

1. The affected coal mine workings or refuse bank will be at negative pressure, relative to ambient; hence little or no fumes will be emitted to the atmosphere except at the fan exhaust points.

2. Accumulation of all the fumes at fan exhaust points will enable postburn incineration of the exhaust to insure complete combustion of carbon monoxide and unburnt soot and hydrocarbons to carbon dioxide and water. If required, scrubber treatment can also be applied to remove air pollutants, such as sulfur dioxide and particulates.

3. Controlled air injection might enable the burn to be carried out under oxidation conditions favorable for sulfur dioxide to react in situ to form solid sulfates, for example, calcium sulfate which would remain in the ground.

4. The heat of combustion of the burning fuel will appear as sensible heat in the exhaust products--perhaps at a temperature as high as 980° C (1,800° F). This heat can be recovered onsite for local use such as production of steam, hot water, process heat, and electricity.

5. The complete burnout of combustible material (carbonaceous material and pyrites) in a mine or waste bank will finally solve the environmental problems of an active fire. In contrast, fires extinguished by wetting and sealing leave wasted coal with its potential for reignition and acid water formation.

6. The solid residue from the complete burnout of a coal refuse bank is red dog, a gravel substitute with commercial value.

The described advantages of burnout control of wasted coal would suggest that the technique could be a panacea for local environmental and energy problems. Although as yet there has been no complete demonstration in an actual abandoned mine and/or waste bank, based on considerations described in the following sections, the technique would appear to be a highly reasonable one.

IN SITU COMBUSTION OF COAL

The Bureau background in burnout control of wasted coals stems from studies on coal mine fires (5) and the underground burning of coal for energy (2, 4). Particularly pertinent are the data from a large-scale sealed trench burn of rubblized Pittsburgh seam coal (4) in which approximately 40 tons of coal rubble (stoker grade) was sealed in a trench to form a simulated underground coal seam approximately 35 feet long, 8 feet high, and 6 feet wide. By means of a metal grate, an axial channel of 1-ft^2 cross section was formed in the coal rubble to define an in situ coal-burning zone. One end of the channel was connected to an insulated exhaust pipe and exhaust fan, and the other end was connected to a valved inlet air pipe. Two other inlet air pipes were also positioned along the channel. The exhaust fan (15,000 std cu ft/min, 18-inch water head capacity), which maintained a negative pressure in the trench, induced an airflow into the channel to sustain the coal burning and at the same time exhausted hot combustion products from the channel. During the 33 hours' duration of the experiment, the thermal output of the in situ combustion process was readily controlled between 1.0 and 1.7 Mw, and the existing combustion products were at very high temperature--about 1,600° C (2,900° F). Except for sulfur dioxide, the exhaust gas was exceptionally clean in terms of low concentrations of carbon monoxide, nitrogen oxides, and particulates. Figure 1 shows data time plots obtained in this experiment from measurements of the flue gas at a position about 20 feet downstream of the channel exit (i.e., following some afterburning with dilution air). It is noteworthy that while the observed sulfur dioxide emission

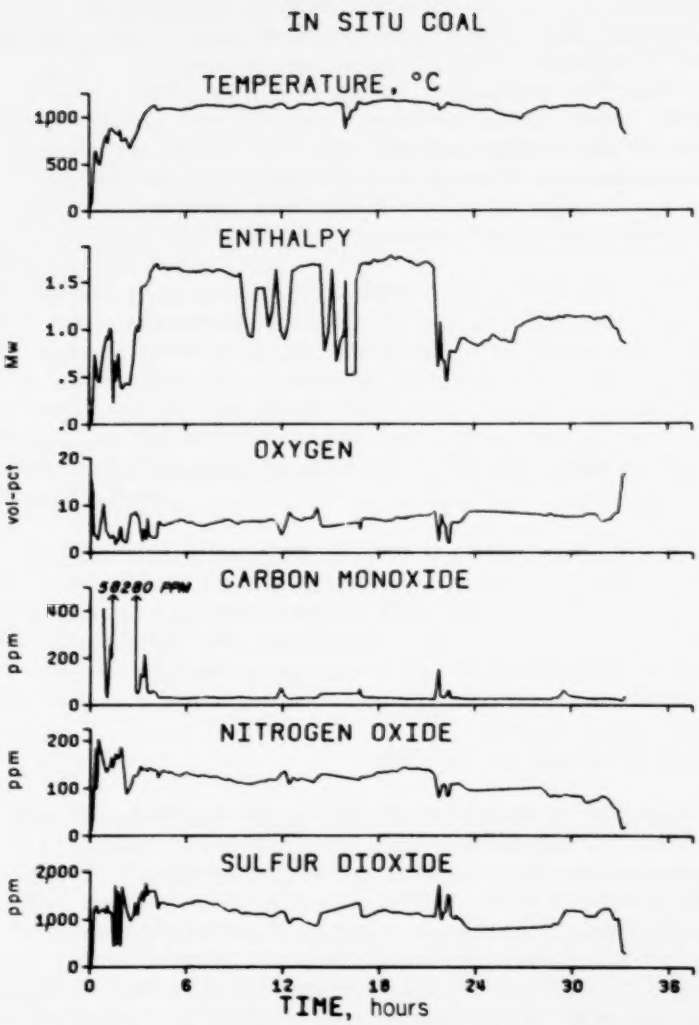


FIGURE 1. - Data time plots for simulated in situ burns of rubblized coal.

(1,100 ppm) is commensurate with the sulfur content of the coal (2 wt-pct), the observed nitrogen oxides emission (110 ppm) is considerably lower than what might be expected on the basis of the fuel-nitrogen content (1.5 wt-pct). The nitrogen oxides emission is actually about a factor of 5 less than values reported for pulverized fuel combustors. Similarly, the particulate emissions appeared to be quite small.[4]

During the entire experiment (ignition, steady burning, and cool-down), the exhaust ventilation control system provided total management of the combustion gasflow. Despite air leakage into the trench and total burnout and cave-in of a portion of the trench, no combustion products escaped to the atmosphere except through the exhaust system. The conclusion was that the controlled in situ burning of coal could be carried out efficiently, cleanly, and with total management of the heat and gases produced. In situ combustion at negative pressure could also be a feasible approach to eliminating the environmental problems of wasted coal fires. Thus, in situ combustion methodology could be applied to accelerate the burning of abandoned mine and waste bank fires simultaneously, with total management of their air pollutant emissions and with utilization of the thermal energy produced--eventually leading to complete burnout of the combustibles and elimination of their potential for acid water formation and reignition.

[4]In a second sealed trench burn test involving a channeled solid block of coal, results similar to the rubblized coal burn were obtained, and in this case the measured particulate emissions averaged only 0.008 lb/10^6 Btu over a 45-hour burning period.

APPLICATION OF IN SITU COMBUSTION TO BURNOUT CONTROL OF WASTED COAL FIRES

Field trials in actual burning waste banks and in abandoned mines--the true test of feasibility--have not yet been attempted. However, a number of technical considerations have been examined, theoretically, using relatively simple models and mathematical treatments of the burnout process. The results, described in this section, support the feasibility of the burnout concept. Some preliminary engineering design data have been obtained, and some important physical parameters have been identified.

Minimum Combustible Content for a Coal Refuse Fire

A given coal refuse pile on fire should be adequate evidence that the refuse contains sufficient combustibles to support burning. However, the composition of most refuse piles is not uniform, having been formed by the dumping of washery plant and mine wastes over a long period of time. The composition of these wastes at any time depends on the quality of the clean coal, usage required (and hence the quality of the reject), and the mining method employed. It is thus useful to estimate what minimum concentration of combustibles is necessary to support a self-propagating accelerated burnout.

To accomplish this goal, the waste bank is considered to consist of the three components: (a) coal, (b) inert matter, and (c) water, and that the in situ combustion process involves no heat loss except for the exhausted flue gas. During steady state propagation of a burn front in the coal refuse, the energy balance for the affected volume of refuse at the front can be written as:

$$\dot{Q}_{rel} = \dot{Q}_{ex} + \dot{Q}_{rem}, \tag{1}$$

where $\dot{Q}_{rel}$ = rate of heat release by combustion of fuel, for example, coal,

$\dot{Q}_{ex}$ = rate of heat exhausted by flue gas removal,

and $\dot{Q}_{rem}$ = rate of heat accumulation in the inert material.

Denoting x_c, x_w, as the initial mass fraction of coal and water, respectively, in the refuse; $\dot{m}_{air}$, $\dot{m}_c$, $\dot{m}_w$ as the mass rates of air injection, coal burning, and water evaporation, respectively; and ΔH_c and ΔH_v as the heat of combustion of coal and heat of evaporation of water, respectively, we have:

$$\dot{Q}_{rel} = \dot{m}_c \Delta H_c, \tag{2}$$

$$\dot{Q}_{ex} = (\dot{m}_c + \dot{m}_w + \dot{m}_{air}) C_p \Delta T + \dot{m}_w \Delta H_v, \tag{3}$$

and $$\dot{Q}_{rem} = (1 - x_c - x_w) \frac{\dot{m}_c}{x_c} C_p \Delta T. \quad (4)$$

A uniform temperature rise, ΔT, and heat capacity, C_p, for all gaseous and solid materials in the burn front are assumed.

Combining equations 1 through 4 yields, after some rearrangement:

$$\Delta H_c + \frac{\dot{m}_w}{\dot{m}_c} \Delta H_v = \left[\frac{\dot{m}_{air}}{\dot{m}_c} \frac{1}{x_c}\right] C_p \Delta T \quad (5)$$

or $$\Delta T = \frac{\left[\frac{H_c}{H_v} - \theta\right] \frac{\Delta H_v}{C_p}}{\phi + \frac{1}{x_c}}, \quad (6)$$

where $\theta = \dot{m}_w/\dot{m}_c = x_w/x_c$, the ratio of mass of water to mass of coal in the refuse.

$\phi = \dot{m}_{air}/\dot{m}_c$, the stoichiometry of the coal combustion process (air/fuel ratio.

The effect of water on the temperature of the combustion process is simply to lower the effective heat of combustion. The effect of coal content on the waste is to alter the effective stoichiometric air/fuel ratio.

It is now interesting to calculate some ΔT values for reasonable estimates of the material parameters. Taking Pittsburgh seam coal at stoichiometric combustion, gives $\phi = 12$ and $\Delta H_c = 7{,}600$ cal/g. The heat of evaporation of water is 540 cal/g. The value chosen for the heat capacity of the mixture in the burn zone (coal, combustion products, water vapor, inert material) is weighted toward a high water vapor content and assumed to be 0.5 cal/g-°C.

Figure 2 shows the calculated combustion temperature for various coal and water contents of the refuse. The boundary line drawn at 800° C (1,472° F) is an estimate of the minimum temperature required for rapid chemical reactions that would insure self-propagating combustion. A typical refuse pile containing 35 pct combustible and an equal amount of water falls into the region of sustained combustion, yielding an exhaust gas of almost 950° C (1,740° F). These calculations indicate that sustained combustion can occur in refuse containing substantial quantities of water (two to three times the coal content). This is consistent with the fact that waste bank fires continue to burn, despite their exposure to the elements and often despite attempts to extinguish them by saturation sprinkling. The calculated results also suggest that most coal refuse piles have enough fuel to sustain a fire, provided that sufficient air can be drawn into the interior of the piles.

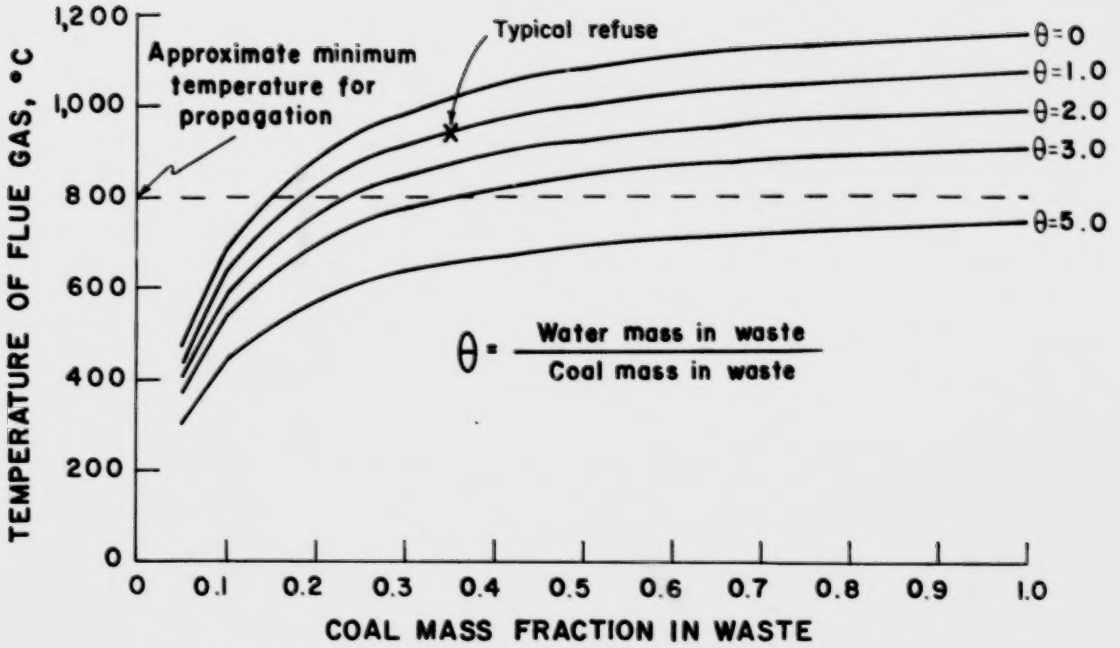


FIGURE 2. - Exhaust temperature as a function of coal and water content.

Heat Loss From Channel Burning in Abandoned Coal Mines

Whereas propagating coal refuse fires results in the accumulation of heat in inert material, which is always intimately mixed with the fuel (i.e., internal to the burning system), the geometry of abandoned mine fires results in heat accumulating in roof and floor strata that are external to the coal burning system. Thus, the heat conducted away from the burning coal must now be considered an energy loss that will affect the exhaust temperatures and could conceivably extinguish burning under certain conditions of seam thickness and channel dimensions. This problem of heat loss during channel burning in a coal seam has received mathematical treatment in a previous Bureau publication (3), and the results pertinent to the problem of burnout of abandoned mine fires are summarized in this section.

The model of channel burning considered is shown in figure 3. A rectangular channel of length (ℓ) and width (w) in a coal seam of thickness (h) moves at a linear surface burning rate (B) through the seam. A constant ventilating air and exhaust gasflow occurs along ℓ. The effective channel width remains constant by the process of continuous coal burning on one side of the channel and continuous or periodic roof fall along the opposite side of the channel. Heat is lost from the system by thermal conduction to the roof and floor strata, but only while the strata define the upper and lower boundaries of the channel. Consideration of the quasi-steady state energy balance during the effective exposure time period leads to:

$$(\Delta T)^{-1} = \frac{C_p(\phi+1)}{\Delta H_c} + \frac{4\lambda}{\rho s \Delta H_c}\sqrt{\frac{w}{\pi\kappa B}}, \qquad (7)$$

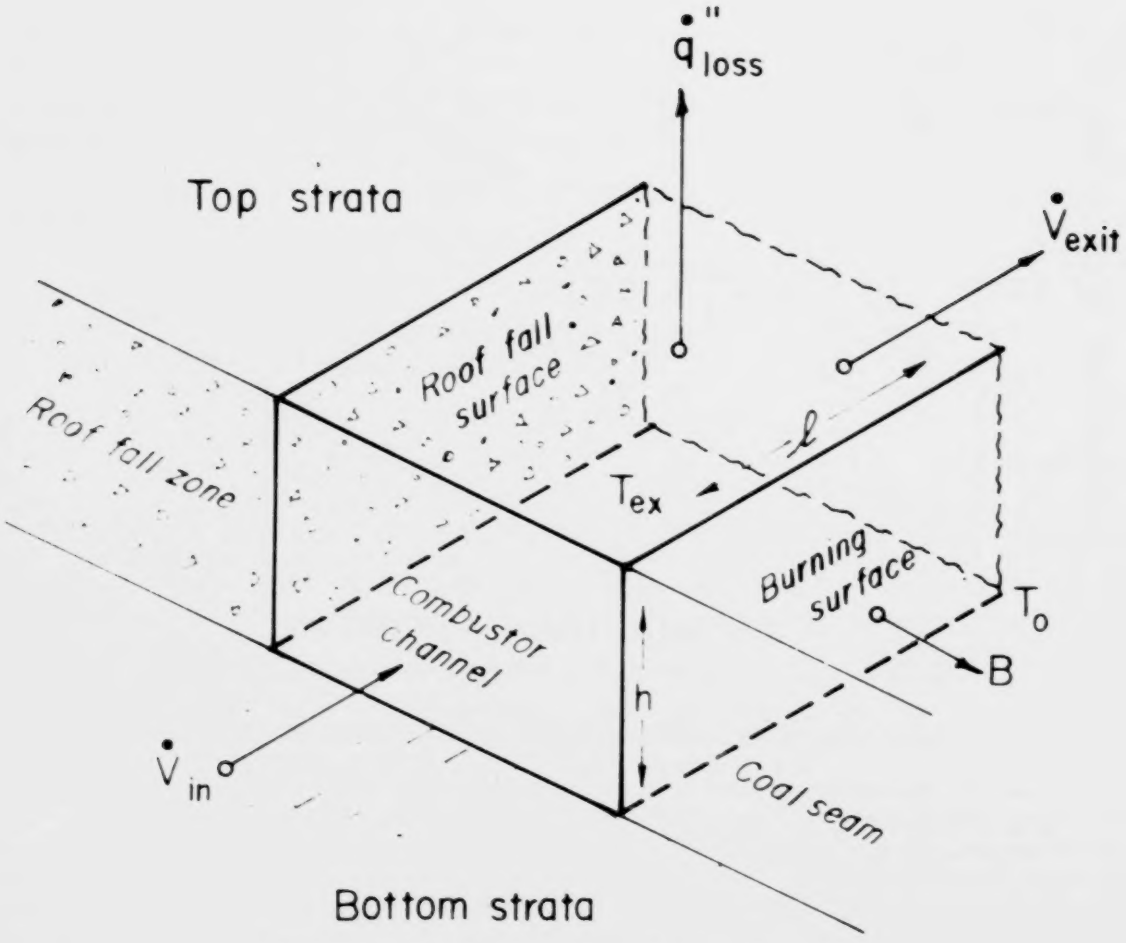


FIGURE 3. - Model coal seam combustion channel.

where λ = the thermal conductivity of the strata (assumed constant),

κ = the thermal diffusivity of the strata,

ρ_s = the density of the strata,

and the remaining symbols have the same definitions given in the previous section.

The fractional heat lost E_L and the fraction of energy transmitted in the exhaust E_H are given by the expressions:

$$E_L = \frac{4\lambda\Delta T}{\rho_s \Delta H_c h} \sqrt{\frac{w}{\pi\kappa B}} \tag{8}$$

and $$E_H = \frac{C_p (\phi + 1)\Delta T}{\Delta H_c} \qquad (9)$$

Equation 8 indicates that the fractional heat loss increases with decreasing seam thickness and with increasing channel width. Figure 4 is a plot of both E_L and ΔT versus the scaling factor $\sqrt{w/h^2}$ for a stoichiometric air and/or fuel ratio, ϕ = 12, and values of the material parameters which are given in table 1. Again, assuming a criterion of $\Delta T > 800°$ C (1,472° F) for self-propagated burning, a heat loss as high as 40 pct could be sustained at a value of $\sqrt{w/h^2} \approx 0.7$ cm$^{-1/2}$. Thus for a 180-cm (6-feet) thick seam, the effective width of the burning channel must be less than 1.6×10^4 cm (530 feet), which would most likely be the case. The temperature criterion (>800° C) would be met even for seams as thin as 30 cm (1 foot). As shown in figure 4, a channel exhaust temperature of 1,000° to 1,200° C (1,800° to

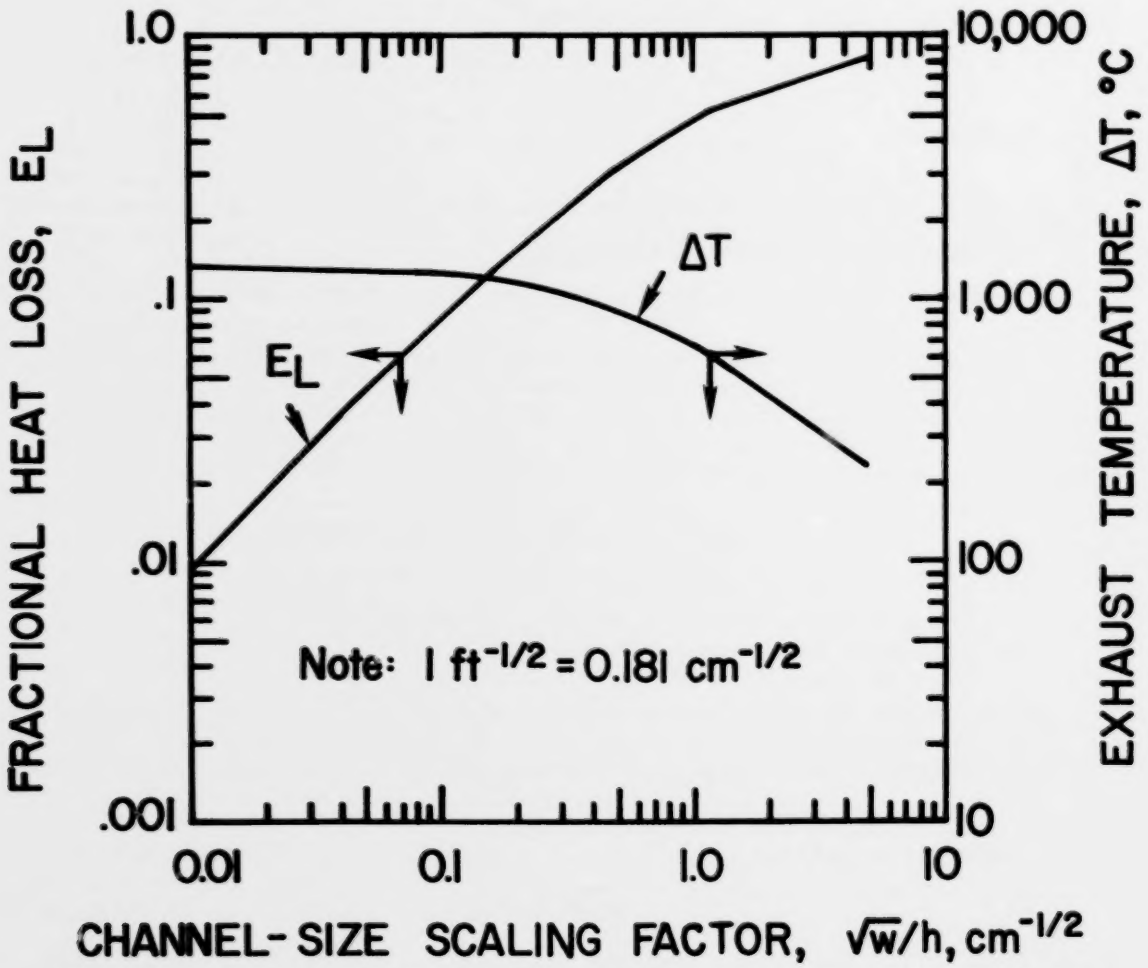
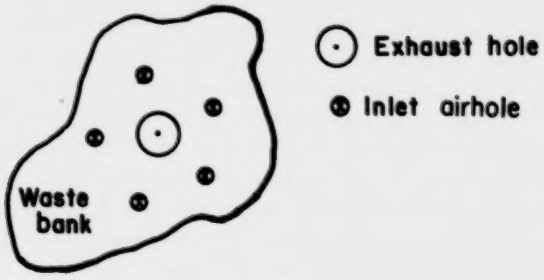


FIGURE 4. - Variation of fractional heat loss and exhaust temperature with channel-size scaling factor.

a. Plan view of multiple borehole system



b. Side view of blind borehole system

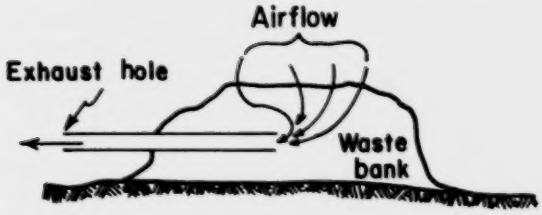


FIGURE 5. - Two possible borehole arrangements.

2,200° F) should be expected, which is in good agreement with the combustion results obtained in some underground coal gasification trials (7).

Effective Burn Control Volume in a Waste Bank

To achieve negative pressure burning in a porous waste bank, it will be necessary to use an exhaust fan operating through a piping system inserted into the bank to suck on a region inside the bank. Figure 5 depicts multiple-inlet air boreholes surrounding a single-exit borehole and a single-exit borehole, with air being drawn through the surface of the bank (blind borehole method). The question is what volume of waste bank can be aerated by exhausting at the exit borehole. This will establish the effective volume of the bank under in situ combustion control. A simple approach to estimating this volume is to apply Darcy's law to the blind borehole geometry, with the assumption that the gasflow within the bank is uniform, steady, and converges spherically toward the tip of the exit borehole.

TABLE 1. - Input data for numerical calculations

Material parameters	Values	
Thermal conductivity of strata...	cal/cm-sec-°C	4×10^{-4}
Linear surface burning rate.....	cm/sec	2×10^{-4}
Heat of combustion of coal.....	cal/g	7×10^{3}
Density of strata.....	g/cm^3	1.3
Heat capacity.....	cal/g-°C	0.4
Thermal diffusivity of strata....	cm^2/sec	10^{-4}

Darcy's equation for one-dimensional steady flow through a porous medium can be written as (15):

$$\dot{q} = \frac{kA}{\mu} (dP/dx). \qquad (10)$$

Where q = the gas volume flow rate in cm^3/sec,

k = the permeability of the porous medium in darcys,

μ = the gas viscosity in centipoise,

A = the effective cross sectional flow area in cm^2,

and dP/dx = the pressure drop across the bed in atm/cm.

A steady flow at the tip of the blind borehole, and uniform convergent flow in the bank requires that $\dot{q}$ be constant across a spherical cross sectional area situated at a distance x from the borehole. If β is the solid angle in steradians which defines the flow region, the cross sectional area as a function of x is:

$$A = 4\pi\beta x^2 \tag{11}$$

and

$$\dot{q} = 4\pi\beta\left(\frac{k}{\mu}\right)x^2\frac{dP}{dx}. \tag{12}$$

With a constant $\dot{q}$, β and (k/μ), equation 12 can be integrated to yield

$$\frac{1}{x_1} - \frac{1}{x_0} = \frac{4\pi\beta}{\dot{q}}\left(\frac{k}{\mu}\right)\left(P_0 - P_1\right). \tag{13}$$

For the porous flow situation being considered, the integration limits can be taken as

$$P_1(x_1) = 1 \text{ atm (ambient pressure)} \tag{14}$$

and

$$P_0(x_0 = d) = \text{maximum negative pressure at one borehole diameter distance, d, away from the tip of the borehole.} \tag{15}$$

This yields the following expression for the affected distance x in the waste bank

$$\frac{1}{x_1} = -4\pi\beta\Delta P\left(\frac{k}{\mu\dot{q}}\right) + \frac{1}{d}, \tag{16}$$

where

ΔP = the effective vacuum (a positive quantity) that can be applied at the exit borehole.

Numerical solutions for x_1 with various sized boreholes are shown in figure 6, for the case where μ = 0.02 cp (i.e., air), ΔP = 0.1 atm (i.e., 1.47 lb/in^2 or 38.6-in H_2O vacuum), and β = 0.5 (i.e., a hemispherical flow region). The numerical solutions in figure 6 are asymptotic.

To achieve large burn volumes, x would have to be large, that is, >300 cm (10 feet), and $\dot{q}/k$ close to the minimum value for which solutions to equation 16 are obtained. In these cases,

$$(\dot{q}/k)_{cr} = \frac{4\pi\beta\Delta Pd}{\mu} \tag{17}$$

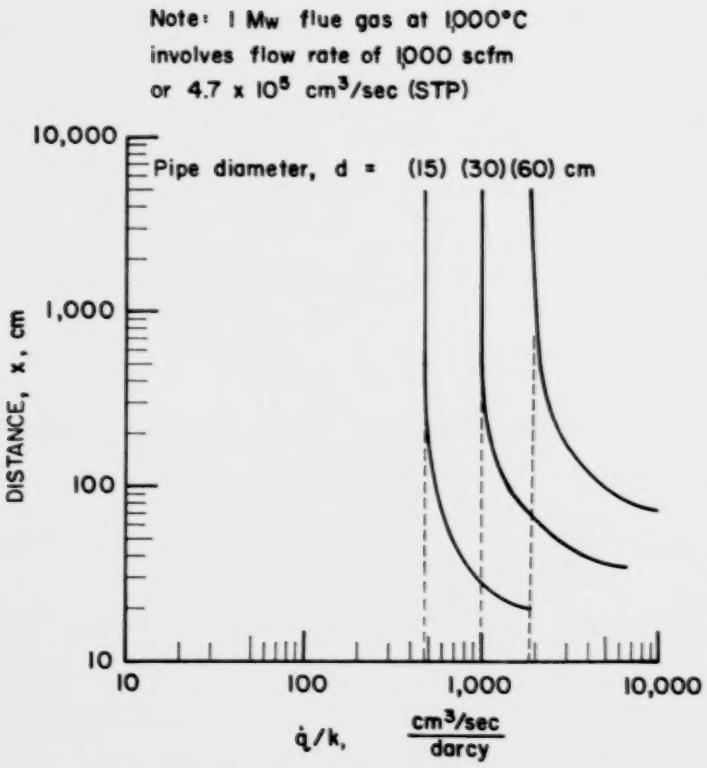


FIGURE 6. - Distance of negative pressure effect in a coal waste pile.

is the asymptotic limit for large x and defines the achievable practical flow rate. For example, in a waste bank having dimensions much larger than d, and having a permeability of 10^3 darcys (approximately 10 times that of a pile of sand), an exhaust flow rate of 10^6 cm^3/sec (2,130 std cu ft/min) could be achieved with a 30-cm (1-foot)-diameter exit borehole. Larger flow rates could be achieved, but only by sacrificing the effective burn volume in the bank. For example, an exhaust flow three times greater (6,390 std cu ft/min or 3 x 10^6 cm^3/sec) from the same bank and borehole leads to a value of x_1 = 100 cm (3 feet). Thus, a blind borehole would have to be positioned about 3 feet below the surface of the bank to maintain a negative pressure burning region, that is, to draw in sufficient air for complete combustion of the waste and exhaustion of the hot gaseous products.

This simple approach to porous flow does not take into account the effects of changing permeability with increasing zonal burnout or the effects of nonuniformities either in the permeability or the gasflow, all of which are expected to occur in an actual bank burnout. However, the calculations do indicate that the maintenance of a negative pressure combustion zone in a porous bank should be feasible, provided that sufficient suction is available from the exhaust fan.

Effective Burn Control Volume in an Abandoned Mine

The burn control volume for an abandoned mine, as in controlled burnout of a waste bank, depends upon the airflow induced by the exhaust fan system. If all the original mine entries and stoppings remained in good condition, simple ventilation network calculations would yield reasonable estimates of the possible airflow, except for old workings on fire where stopping and roof collapse have undoubtedly occurred. However, for the current purposes, abandoned mine fire geometry is idealized as the propagating channel burn depicted in figure 3. This will enable some estimate of the relationship between

channel size and ventilation fan requirements. The calculations presented draw heavily on Bureau results previously reported in connection with in situ coal combustion and coal mine fires (2-5).

Referring to figure 3, the total mass rate of coal burning is

$$\dot{M}_t = \rho_s B A_s, \tag{18}$$

where ρ_s = the coal density,

B = its constant linear burning rate (identical to the rate of movement of the channel through the coal seam),

and $A_s = h\ell$ is the area of the burning coal surface. For a stoichiometry defined by an air/fuel ratio of ϕ, the total volumetric exhaust flow rate is

$$\dot{q} = \frac{\rho_s B(\phi+1)A_s}{\overline{M}/\overline{V}}, \tag{19}$$

where $\overline{M}$ = the average gram molecular weight of the gaseous combustion products,

and $\overline{V}$ = their specific molar volume.

From previous Bureau studies (4), the pressure drop across the burning channel is estimated to be

$$\Delta P = \frac{\alpha \ell \dot{Q}_{ex}^2}{A_x^{5/2}} \qquad \text{cm-H}_2\text{O}, \tag{20}$$

where ℓ (cm) = the channel length,

A_x (cm^2) = its cross sectional area,

$\dot{Q}_{ex}$ = the thermal power level of the exhaust flow in kilowatts,

and α = an empirical constant equal to 0.17 for the given parameter units.

Since $$\dot{Q}_{ex} = \rho_s B A_s \Delta H_c, \tag{21}$$

where ΔH_c is the heat of combustion of coal, we obtain from equations 20 and 21,

$$\frac{\Delta P}{\ell} = \alpha(\rho_s B \Delta H_c)^2 \frac{A_s^2}{A_x^{5/2}} \tag{22}$$

and $$\Delta P = \alpha(\rho_s B \Delta H_c)^2 \frac{\ell^3}{h^{1/2} w^{5/2}}. \tag{23}$$

For the coal parameters in table 1 (keeping in mind that for $\alpha = 0.17$, the ΔH_c of 7×10^3 cal/g must be expressed as 239 kw-sec/g), and assuming that $h^{1/2} w^{5/2} \simeq w^3$ (which would be exactly the case for a square channel with $h = w = A_x^{1/2}$), equation 23 becomes

$$\Delta P = 6.6 \times 10^{-4} \left(\frac{\ell}{w}\right)^3 \quad \text{cm-H}_2\text{O}. \tag{24}$$

Here the pressure drop is very sensitive to the ratio of channel length to channel width. For example, an $\ell/w = 25$ would require a ΔP of 10.3 cm-H_2O (0.15 lb/in^2), which should be readily achieved with conventional exhaust fans. However an $\ell/w = 75$ leads to a ΔP of 278 cm-H_2O (4.2 lb/in^2) which would pose a more severe constraint on fan size.

To relate equation 24 to burning volume, the effective width of the burning channel must be known, a matter which is probably site-selective. A reasonable estimate would be w no less than one-half the seam thickness, which for a 180-cm (6-feet) thick bed and a nominal ΔP of 10.3 cm-H_2O, would lead to a ventilated burn channel length of 2,250 cm (75 feet).

The exhaust volume is given by equation 19, which for reasonable material parameter values, $\phi = 12$; $\overline{M} = 30$ g/mole; $\overline{V} = 2.24 \times 10^4$ cm^3/mole standard temperature and pressure (STP). Also table 1 yields

$$\dot{q} = 2.52\, A_s = 2.52\, (h\ell) \text{ cm}^3/\text{sec (STP)} \tag{25}$$

For the channel burning case above where h = 180 cm, ℓ = 2,250 cm, ΔP = 10.3 cm-H_2O, the volumetric flow rate would be 10^6 cm^3/sec (STP) or 2,190 std cu ft/min, well within the range of conventional exhaust fans. At 1,000° C (1,830 ° F), the power level generated by the exhaust flow would be $\sim$2 Mw (e.g., equation 13). The fan air horsepower, which is the product of ΔP and $\dot{q}$ multiplied by an appropriate conversion factor, would in this case be 1.4 air horsepower (ahp), again a very nominal value. The fan power requirements are discussed in somewhat greater detail in the next section. These theoretical results are based on a highly idealized in situ burning geometry, for in abandoned mines, channel blockages and roof cave-ins could easily affect the ventilation pressure drop and the ventilation airflow to the burning coal surface. However, on the basis of the idealized geometry, there appear to be no fundamental difficulties in achieving ventilation-controlled burnout of the combustible in an abandoned mine.

Fan Power Requirements for Burnout Control

Although the design of an exhaust fan ventilation system for burnout control will have to be site-selective, it is useful to establish some general requirements in engineering units for fan capacity and motor size. This is necessary to elucidate the value of the energy conversion efficiency that is available through in situ combustion techniques.

Assume coal to have a heating value of 10,000 Btu/lb (5.55 kcal/g) and a nominal carbon to hydrogen ratio of unity. The complete combustion reaction can be approximated by

$$\underbrace{CH}_{\text{1 mole coal}} + \underbrace{1.25O_2 + 4.62N_2}_{\text{5.87 moles air}} \longrightarrow \underbrace{CO_2 + \tfrac{1}{2}H_2O + 4.62N_2}_{\text{6.12 moles exhaust}}.$$

From molecular weight considerations, it is readily seen that 0.388 pound of air (5.87 moles or 4.7 std ft^3) is required to combust 0.0286 pound of coal. This leads to 6.12 moles of gaseous exhaust (4.9 std ft^3), having a sensible heat content of 58.4 Btu/ft^3 (STP).

We now consider an exhaust thermal power output of 1 Mw (or 5.7×10^4 Btu/min). This requires an exhaust flow rate of combustion products of 976 std cu ft/min, and a coal combustion rate of 5.7 lb/min.

The air horsepower required to drive this exhaust flow is given by (6)

$$\text{ahp} = \frac{P(\text{in-}H_2O) \times \dot{q}(\text{scfm})}{6{,}348}. \qquad (26)$$

If we assume that a relatively high pressure drop of 100 in-H_2O (3.8 lb/in^2) will be required to ventilate the required burn control volume, the fan air horsepower requirements for a 1 Mw thermal output is 15.4 ahp. With 70-pct fan efficiency, the electrical power requirement for the fan motor will be 22 hp (or 0.0164 Mw). Assuming no losses or additional energy expenditure (e.g., for scrubbing systems, thermal conversion systems), the energy recovery for the in situ combustion technique would be

$$\frac{\text{thermal energy output}}{\text{electrical energy input}} = 61.$$

This factor, which is independent of $\dot{Q}_{ex}$, is considerably greater than the value of 3 to 4 reported for underground coal gasification (14). Even when a thermal to electrical energy conversion efficiency of about 30 pct is taken into account, the energy recovery factor is still quite large, that is,

$$\frac{\text{thermal energy output}}{\text{thermal equivalent electrical energy input}} = 20.$$

Thermal losses would, of course, lower the recovery factor by a proportional amount, but on the other hand, decreased fan pressure requirements (i.e., ΔP <100 in-H_2O) would increase the recovery factor proportionally.

Surface Transport of Hot Exhaust Products

The technical discussions have so far centered on the in situ combustion process and not on the utilization of heat produced during burnout. In general, the approach to utilization of heat would be nearly the same as almost any high-temperature, ∿1,000° C (∿1,830° F), ambient-pressure flue gas, for example, to supply process heat, utility steam, electricity generation.

However, utilization or conversion would have to be onsite because it is not feasible to transport heat energy over long distances. Questions still arise as to what distance would be defined as onsite, or how far the hot flue gas can be moved before thermal losses, and exhaust pipeline costs become prohibitive. In essence, this will define the maximum distance between the exit borehole and the energy utilization facility. Estimates of this maximum distance and its parametric relationship to thermal power level and pipeline size are readily obtained from considerations of heat loss and pressure drop through the surface pipe system.

For the heat loss calculation, we consider the steady state radial flow of heat into a pipe wall of thickness σ whose inner surface is maintained at constant temperature T_a, and whose outer surface temperature is at constant ambient temperature T_o. For a pipe wall having constant thermal physical properties, the rate of heat flow per unit length of pipe, $\dot{Q}'_a$ is given (1) by

$$\dot{Q}'_a = \frac{2\pi\lambda_p (T_a - T_o)}{\ln(1+\sigma/a)}, \tag{27}$$

where λp = the thermal conductivity of the pipe wall,

a = the inside radius of the pipe,

and σ = the wall thickness.

For a small section of pipe having a length $\Delta L = (L_2 - L_1)$ and an axial temperature difference defined by $T_a(L_1) = T_1$ and $T_a(L_2) = T_2$, the total rate of heat loss to the wall will be determined by equation 27, using an average inner-surface temperature

$$\overline{T}_a = (T_1 + T_2)/2 = T_1 - \Delta T/2 \tag{28}$$

for the section ΔL. Here, $\Delta T = T_2 - T_1$ is the change in temperature across the section ΔL. Assuming a uniform and well-mixed hot gasflow through the pipe, ΔT is also the change in temperature of the gas owing to the wall heat loss.

The energy balance for the pipe section ΔL is then

$$\frac{2\pi\lambda_p}{\ln(1+\sigma/a)} (T_1 - T_0 - \Delta T/2)(\Delta L) = -\dot{m}_g C_p (\Delta T), \tag{29}$$

where $\dot{m}_g$ = the mass flow rate of the gas,

and C_p = its specific heat.

Solving for $\Delta T/\Delta L$ in the zero limit of ΔL yields a simple differential equation

$$dT/dL = \frac{-2\pi\lambda p (T_1 - T_0)}{\dot{m}_g C_p \ln(1+\sigma/a)} \tag{30}$$

for the change in gas temperature with pipe length. Integrating between the limits $T(L = 0) = T_{ex}$, the exit borehole exhaust temperature, and $T(L) = T_L$, the gas temperature at distance L along the pipe, we obtain

$$\frac{T_L - T_0}{T_{ex} - T_0} = \exp\left[-\frac{2\pi\lambda_p L}{\dot{m}_g C_p \ln(1+\sigma/a)}\right]. \tag{31}$$

Recognizing that $\dot{Q}_L = \dot{m}_g C_p (T_L - T_0)$, it is seen that the left-hand side of equation 31 is also the fraction of the exhaust thermal power flowing through the pipe at distance L (i.e., $E_H = Q_L/Q_{ex}$). Equation 31 can also be written as

$$E_H = \exp\left[-\frac{2\pi\lambda_p (T_{ex} - T_0)L}{\dot{Q}_{ex} \ln(1+\sigma/a)}\right]. \tag{32}$$

The thermal transport efficiency increases exponentially, with increasing power level and decreasing gas temperature. Figure 7 depicts several curves of E_H versus L for various power levels of flue gas at T_{ex} = 1,000° C (1,830° F), and various values of the pipe size factor σ/a. As expected, the transport efficiency depends strongly on Q_{ex}, σ/a, and L.

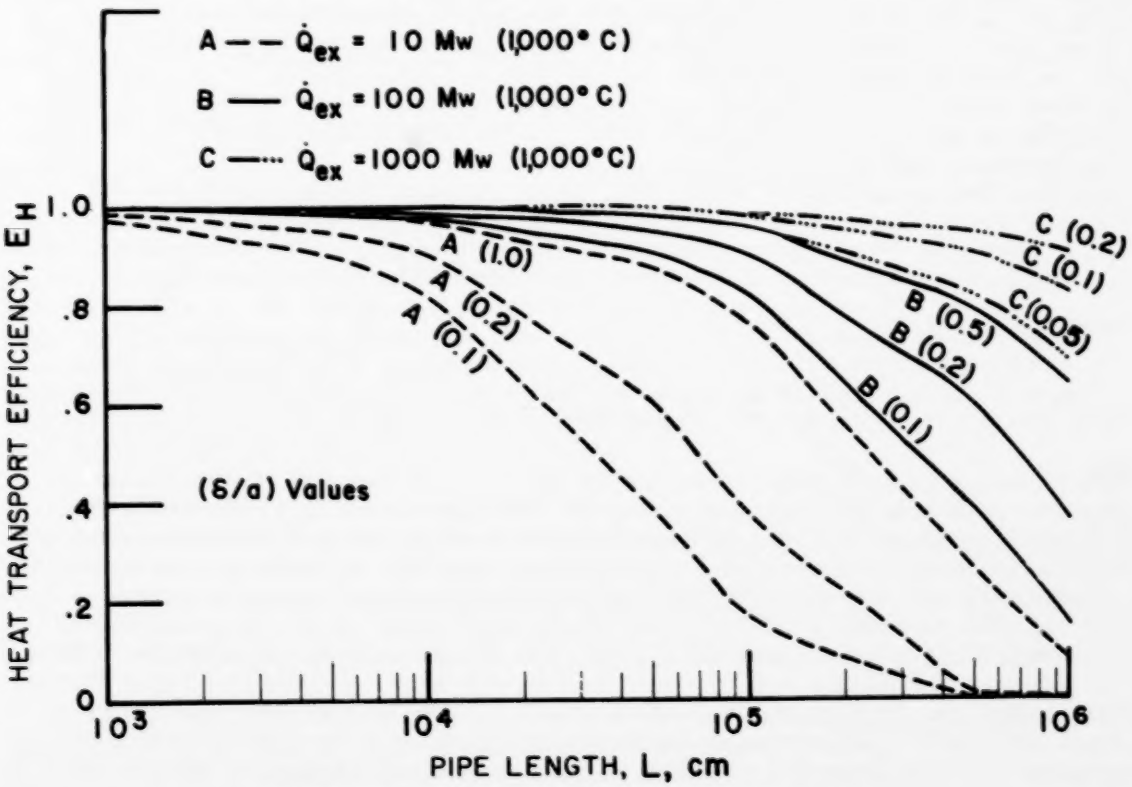


FIGURE 7. - Efficiency of heat transport in a pipe.

Assuming that a value of $\sigma/a = 0.1$ to 0.2 might be reasonable, it can be seen that 10-, 100-, and 1,000-Mw power levels could be effectively transported 10^4 cm (328 feet), 10^5 cm (3,280 feet), and 10^6 cm (32,800 feet), respectively, before heat loss becomes excessive.

Considering pipe heat loss alone, the combustion products from a controlled burnout of wasted coal could be transported an adequate distance for onsite utilization, particularly at the higher power levels. However, the pressure drop associated with a desired gasflow rate or thermal power level is another important constraint.

To estimate the pressure drop ΔP for a given hot gasflow we considered the pipe flow equation (15)

$$\Delta P = \frac{f}{2} \rho v^2 \frac{A_w}{A_x}, \tag{33}$$

where ρ and v = the gas density and gas velocity, respectively;

A_w and A_x = the pipe-wetted surface area and cross sectional area, respectively,

and f = a wall friction factor which is dimensionless when the parameter values are expressed in the centimeter-gram-second system of units.

For a circular pipe $A_w/A_x = 2\pi aL/\pi a^2$, and recognizing that the total steady state mass flow rate $\dot{m}_g$ is

$$\dot{m}_g = \rho v A_x = \frac{\dot{Q}_{ex}}{C_p (T_{ex} - T_0)}, \tag{34}$$

equation 33 becomes

$$\Delta P = \frac{f}{\rho} \left[\frac{\dot{Q}_{ex}}{\pi C_p (T_{ex} - T_0)} \right]^2 \frac{L}{a^5}. \tag{35}$$

The pressure drop is very sensitive to the pipe radius and thermal power level. ΔP decreases with increasing 'a' and decreasing $\dot{Q}_{ex}$. On the other hand from equation 32, the thermal transport efficiency, E_H, increases with decreasing 'a' and increasing $\dot{Q}_{ex}$. Thus both ΔP and E_H must be considered together in setting specifications for the surface heat transport pipe.

Equation 35 is plotted in figure 8 as ΔP versus L for some power levels of interest assuming $f = 0.01$, that is, smooth wall, turbulent flows. For a 100 cm-H_2O (36 in H_2O) pressure drop and a 10^5-cm (3,280-foot) distance, a 10-, 100-, and 1,000 Mw-power level would require a pipe radius of 45, 113, and 288 cm, respectively. An 80-pct heat transport efficiency under these same conditions would require the wall thickness of the pipe to be approximately 50, 10, and 2 cm, respectively.

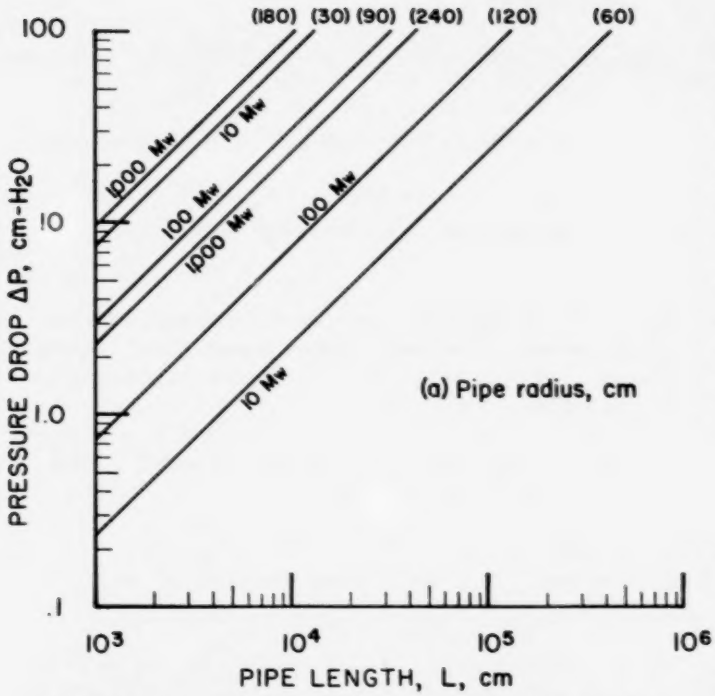


FIGURE 8. - Pressure drop versus pipe distance for transporting thermal power.

From these considerations, it can be expected that piping cost for surface transportation of high-temperature flue gas will be significant even with onsite utilization. The economic benefits of doing so will depend very strongly on the power levels to be transported, the actual onsite distances involved, and of course the effective market value of the energy when utilized.

CONCLUSIONS

A plan for burnout of wasted coals has been prescribed, and some of the technical factors that will influence the design of an in situ combustion system for a controlled burnout have been discussed. These factors show that if the burnout control concept can be successfully applied to existing fires in abandoned coal mines and waste banks, a significant advance will have been made toward solving the environmental, public safety, and public nuisance problems associated with such fires. The theoretical considerations of combustible concentrations, heat losses, and pressure drops support feasibility arguments for accelerating burning of mined-out workings and coal refuse piles under negative pressure. Data from the operation of a large-scale simulated in situ coal combustor support the idea that burnout control can be accomplished with total management of air pollutant emissions and with effective utilization of the sensible heat of the gaseous combustion products.

Questions still to be answered on the long-term control of a burnout system are (1) what are the effects of crevices and channels on the waste bank permeability and the effective burn volume; (2) what are the effects of roof falls on the pressure drop requirements for burning mined-out entries, and would this lead to deterioration of the combustion efficiency; and (3) what surface subsidence effects will be experienced from complete burnout?

These questions are important, but they are site-selective and can only be answered through field trials in actual abandoned coal mines and in coal waste banks. As such, the real world becomes the required laboratory for experimentation, and although full-scale fieldwork is both expensive and time consuming, the results once obtained are meaningful, directly applicable, and conclusive.

REFERENCES

1. Carslaw, H. S., and J. C. Jaeger. Conduction of Heat in Solids. Oxford Univ. Press, London, 1947, p. 167.

2. Chaiken, R. F. In Situ Combustion of Coal for Energy. BuMines TPR 84, 1974, 12 pp.

3. _____. Heat Balance in In Situ Combustion. BuMines RI 8221, 1977, 11 pp.

4. Chaiken, R. F., L. E. Dalverny, M. E. Harris, and J. M. Singer. Simulated In Situ Coal Combustion Experiment. 4th Ann. Underground Coal Conversion Symp., Steamboat Springs, Colo., July 1978. Sandia Laboratories, Albuquerque, New Mex., pp. 515-526.

5. Chaiken, R. F., J. M. Singer, and C. K. Lee. Model Coal Tunnel Fires in Ventilation Flow. BuMines RI 8355, 1979, 32 pp.

6. Cummins, A. B. SME Mining Engineering Handbook, v. 1. American Institute of Mining, Metallurgical, and Petroleum Engineers, Inc., Baltimore, Md., 1973, pp. 16-24.

7. Elder, J. L., M. H. Fies, H. G. Graham, R. C. Montgomery, L. D. Schmidt, and E. T. Wilkins. The Second Underground Gasification Experiment at Gorgas, Ala. BuMines RI 4808, 1951, 72 pp.

8. Griffith, F. E., M. O. Magnuson, and G. J. R. Toothman. Control of Fires in Inactive Coal Formations in the United States. BuMines Bull. 590, 1960, 105 pp.

9. Johnson, W., and G. C. Miller. Abandoned Coal-Mined Lands--Nature, Extent, and Cost of Reclamation. BuMines Spec. Pub. 6-79, 1979, 29 pp.

10. Magnuson, M. O. Control of Fires in Abandoned Mines in the Eastern Bituminous Region of the United States. A Supplement to Bulletin 590. BuMines IC 8620, 1974, 53 pp.

11. Magnuson, M. O., and E. C. Baker. State-of-the-Art in Extinguishing Refuse Pile Fires. 1st Symp. on Mine and Preparation Plant Refuse Disposal. Nat. Coal Assoc., Coal and the Environment Tech. Conf., Louisville, Ky., October 1974, pp. 165-182.

12. McNay, L. M. Coal Refuse Fires, An Environmental Hazard. BuMines IC 8515, 1971, 50 pp.

13. Myers, J. W., J. J. Pfeiffer, E. M. Murphy, and F. E. Griffith. Ignition and Control of Burning of Coal Mine Refuse. BuMines RI 6758, 1966, 24 pp.

14. Schrider, L. A., C. F. Brandenburg, D. D. Fischer, R. M. Boyd, and G. G. Campbell. The Outlook for Underground Coal Gasification. Preprint of paper pres. at the Lignite Symp., Grand Forks, N. Dak., May 1975, 31 pp; available from U.S. Department of Energy, Laramie (Wyo.) Energy Technology Center.

15. Streeter, V. L. Handbook of Fluid Dynamics. McGraw-Hill Book Co., New York, 1961, pp. 16-3 and 3-10.

☆U.S. GOVERNMENT PRINTING OFFICE: 1980-603-102/101

INT.-BU.OF MINES,PGH.,PA. 24821